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博 士 学 位 论 文

大场景车载激光点云三维目标检测算法研究

Research on Three-dimensional Object Detection from Large-scale Mobile Laser Scanning Point Clouds

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摘要

随着激光扫描技术和组合定位定姿技术的不断发展，快速获取大场景三维信息已经成为现实。车载移动激光扫描系统以其独特的系统优势，能够快速获取大范围场景的高密度、高精度以及具有地物三维地理坐标的三维点云数据。车载移动激光扫描系统采用主动式近红外激光测量方式，数据采集任务不受任何环境光照条件的影响，在白天或夜间均可进行场景数据采集。车载移动激光扫描系统及其三维点云数据已被广泛地应用于交通运输、道路规划、道路检修、地图导航、数字城市、文物保护、林业、采矿业、影视动漫以及基础测绘等领域。基于三维点云数据的三维目标检测算法的研究也已取得了重大的进展。然而，现有的三维目标检测算法在处理大场景车载激光点云数据时仍然存在以下几个问题：（１）时间复杂度较高或计算效率较低；（２）特征表达能力不足；（３）精度较低、鲁棒性较差；（４）数据的不完备性。另外，由于车载激光点云的高密度、海量特性、空间离散特性以及自然场景中三维目标的数据不完整性、目标间的重叠性、遮挡性、相似性等现象，研究鲁棒、高效的三维目标检测算法对进一步推广车载移动激光扫描系统及其数据在各个领域的应用都具有重要的意义。本文针对大场景车载激光点云三维目标检测所面临的科学和算法问题，主要围绕以下三个内容进行研究：

首先，针对现有特征点描述方法只能描述特征点的局部特征以及缺乏针对局部点云块整体特征描述的问题，提出了三维点云特征描述的新方法。针对基于形状匹配的三维目标检测，提出了用于描述三维点云目标整体结构特征的成对三维形状上下文。通过构造邻近特征点对之间的成对三维形状上下文，可以对三维目标的局部特征进行描述。通过构造三维目标上所有特征点对之间的成对三维形状上下文，可以对三维目标的整体结构特征进行描述。此外，针对基于目标局部特征的三维目标检测，提出了用于描述局部点云块高阶抽象特征的多层结构特征生成模型。该模型通过深度学习方法进行构造，能够快速、高显著性、高可区分性地对局部点云块进行高阶特征描述。

其次，针对实际三维点云场景中同类目标之间的尺寸多样性、空间拓扑结构多样性以及目标重叠问题，提出了基于三维点云数据的三维目标匹配框架。该框架通过特征匹配项和几何匹配项分别对三维目标的局部特征和几何结构特征进行约束。通过构造局部仿射不变性几何约束，该三维目标匹配框架不仅能够有效地处理不

同尺寸、不同空间拓扑结构的同类三维目标，而且对包含附属物或与其他目标重叠的三维目标也能取得理想的匹配结果。

最后，针对实际三维点云场景中不同语义目标之间的重叠性以及车辆目标之间的不同程度数据完整性问题，提出了基于霍夫森林模型和可见性估计模型的三维车辆检测算法。霍夫森林模型能够有效地将局部点云块的特征表示映射到三维车辆的质心位置，实现基于车辆局部特征的三维车辆检测。可见性估计模型通过车辆组件部分的分布信息，能够有效地对三维车辆的完整性进行估计，用以增强数据覆盖不完整车辆目标的存在性的概率估计结果。

本文在大场景车载激光点云测试数据集上对所提出的三种三维目标检测算法的检测性能和计算性能进行了测试与定量分析。结果表明，本文所提出的三维目标检测算法能够有效地处理大场景车载激光点云数据，并且取得了较为理想的三维目标检测性能。另外，与现有的三维目标检测算法的对比结果同样表明了本文所提出的三维目标检测算法的优越性。本博士课题的研究对大场景车载激光点云三维目标检测算法的研究起到了重要的推动作用。

关键词：移动激光扫描；三维目标检测；特征描述符；三维目标匹配；深度学习；霍夫森林

Abstract

With the increasing development of laser scanning and position and orientation technologies, it has been a reality to rapidly acquire three-dimensional (3D) information of large-scale natural scenes. Due to the superior properties, mobile laser scanning (MLS) systems can rapidly collect highly dense and accurate 3D point clouds of real-world coordinates over large areas within a short time period. MLS systems, an active mapping system, use near-infrared laser beams to measure objects' topologies. Mapping missions can be carried out in the daytime or nighttime without the consideration of environmental illuminations. MLS systems and the resultant 3D point clouds have been extensively used in fields of transportation, road planning, road maintenance, map navigation, digital city, heritage documentation, forestry, mining, animation, basic surveying and mapping, etc. Consequently, studies on 3D object detection from 3D point clouds have also achieved great improvements. However, existing algorithms on 3D object detection from large-scale MLS point clouds still remain the following disadvantages: (1) high computional complexity or low computational efficiency, (2) lack of effective feature descriptors, (3) low accuracy and robustness, and (4) data incompleteness. In addition, due to the properties of high density, large volume, and spatial discreteness of MLS point clouds, as well as the incompleteness, overlaping, sheltering, and similarity of 3D objects in actual point cloud scenes, it is greately important to exploit robust and effective 3D object detection algorithms to expand the applications of MLS systems and 3D MLS point clouds. To solve the problems in 3D object detection from large-scale MLS point clouds, this doctoral dissertation mainly focuses on the following three aspects:

Firstly, considering the problems of existing feature descriptors in characterizing only local features and lack of effective feature descriptors for depicting local point cloud segments, novel feature descriptors are proposed. For shape-based 3D object detection purposes, a pairwise 3D shape context is proposed to model the entire structures of 3D objects. Specifically, by constructing pairwise 3D shape contexts for nearby feature point pairs, the local features of 3D objects can be well modeled. By constructing pairwise 3D shape contexts for all pairs of feature points, the entire structures of 3D objects can be

well modeled. In addition, for local part-based 3D object detection purposes, a multi-layer feature generation model is proposed to abstract high-order feature representations of local point cloud segments. Constructed based on deep learning techniques, the multi-layer feature generation model can rapidly generate highly salient, highly distinctive, and high-order feature representations for local point cloud segments.

Secondly, considering the problems of scale variance, topology variance, and overlapping of 3D objects in actual point cloud scenes, a novel 3D object matching framework is proposed for matching 3D point cloud objects. This framework uses feature matching and geometric matching terms to respectively constrain the local features and geometric structures of 3D objects. By constructing locally affine-invariant geometric constraints, this framework can not only handle 3D objects of varying scales and topologies, but also obtain promising matching performance for 3D objects with attachments or overlapped with other objects.

Finally, considering the problems of overlapping and different levels of incompleteness of 3D cars in actual point cloud scenes, a Hough forest model and a visibility estimation model are proposed for 3D car detection. Hough forest model can effectively map feature representations of local point cloud segments to the locations of cars' centroids. Based on the part component distributions of 3D cars, visibility estimation model can effectively estimate the completeness of 3D cars to augment the estimation probability of the exisitence of 3D cars.

The eximantions and quantitative evaluations of the three proposed 3D object detection algorithms on large-scale MLS point cloud data sets demonstrate that the proposed algorithms can effectively handle large-scale MLS point clouds and achieve promising detection performances. In addition, the comparative studies with existing 3D object detection algorithms also demonstrate the superior performance of the proposed algorithms. The studies in this doctoral dissertation make a significant contribution to the development of 3D object detection algorithms on large-scale MLS point clouds.

Keywords: Mobile laser scanning; 3D object detection; Feature descriptor; 3D object matching; Deep learning; Hough forest

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